Laser Irradiation of Biological Tissue Through Water as a Means of Reducing Thermal Damage

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Background and Objective: **Reduction of thermal damage inbred with laser surgery is an ongoing challenge. The cavitation effect has been shown to facilitate the transmission of a laser beam through the otherwise opaque water layer. We suggest that by immersing the target tissue in water during laser surgery, thermal damage will be diminished.**
Study Design/Materials and Methods: **A method of irradiating tissue by CO_2 laser through a layer of a few millimeters of water is described. A series of experiments was conducted on fresh bovine cornea immersed in water or in air, histology of thermal damage was compared.**
Results: **We were able to show that irradiation of tissue immersed in water reduces the thermal damage caused to the area surrounding the incision as compared to the damage caused during irradiation of tissue in air ($P < 0.001$).**
Conclusion: **Laser surgery of tissue immersed in water can reduce the inbred thermal damage. Application of this method to clinical use may result in precise, clean cutting, and enable the use of CO_2 laser through water.**

Key words: cavitation effect, laser surgery, thermal damage

INTRODUCTION

One of the problems related to the application of the CO_2 laser in surgery is the thermally damaged layer surrounding the incision created by the laser beam. This damage is usually dealt with by optimizing the laser beam parameters [1–4]. In this paper we propose an additional simple method of reducing thermal damage by immersing the irradiated tissue in water, in order to provide an environment which removes heat with greater efficiency and filters the laser beam.

When a laser beam impinges on biological tissue, it can either be scattered or absorbed. The light which is absorbed is converted into the energy that is available for the procedure we wish to perform [5]. The form of this energy determines the type of laser-tissue interaction which will take place [6]. In all applications of the CO_2 laser which involve tissue removal, a layer of thermally damaged tissue is formed around the incision. Heat transport to tissue which is not directly in the beam path as well as the lower energy "tails" of the Gaussian beam, deposit energy in tissue cells which is not sufficient to cause ablation, but may cause cell denaturation or blood coagulation, thus forming a region of thermal damage. A major effort is applied to develop methods for reducing its dimensions. The basic approach has been to seek optimal irradiation parameters for the laser beam, and it has been found that using pulsed laser beams and a "top hat" profile helps to reduce the thermal damage surrounding the incision [1–4]. Using pulse durations shorter

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than 1 Msec, such as those provided by the TEA-CO_2 or Excimer laser, allows cooling of the tissue between pulses, thus preventing accumulation of heat. However, these lasers are expensive and difficult to operate. A more practical approach would be to cool the tissue both before and after irradiation by a conventional, easy to use CO_2 laser [7,8]. This is done using cold water or air. However because of the high absorbency of the 10.6 m radiation in water, no attempt has been made to cool tissue during the irradiation process itself.

The purpose of the present work is to offer a way to transmit the laser beam through an opaque liquid by a method called the "cavitation" effect [9]. At the same time, it allows for tissue cooling with water during the irradiation process, which may help reduce thermal damage. This approach will also facilitate procedures in a liquid environment such as angioplasty and urologic endoscopic surgery.

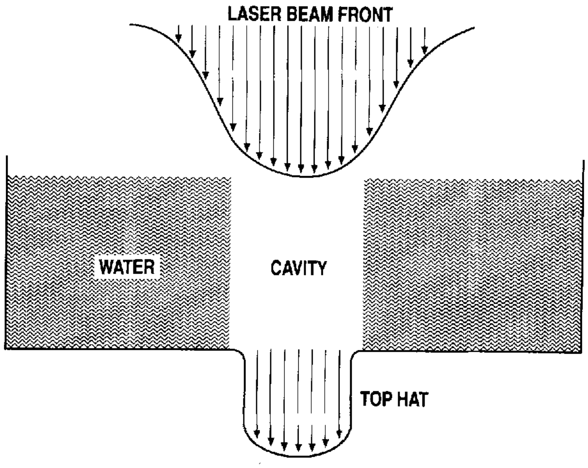

Fig. 1. A laser beam passing through an opaque liquid via a cavity. Part of the energy of the beam is used to create the cavity and the rest is transmitted through it. The beam front changes its shape from Gaussian to "top hat" configuration.

The Cavitation Effect

The cavitation effect involves creating a tunnel through a layer of opaque liquid thus allowing the laser beam to pass. Part of the beam energy is used to create the tunnel, or "cavity", and the rest is transmitted as shown in Figure 1. We have found that the cavitation effect can be achieved using trains of laser pulses satisfying the following conditions: Short extinction length in the liquid, high energy per pulse and high repetition rates [9]. A simplified model describing the formation of these cavities has been presented and tested experimentally [9,10]. Simply stated, two opposing processes take place when a train of laser pulses impinges on water; during the laser pulse, when the laser radiation is "on," water is removed off the surface of the liquid creating a small crater. Between pulses, when the laser radiation is "off," the liquid tends to fill the recently created crater. It is the balance between the rate of liquid removal and the filling of the cavity that determines the condition for maintaining an open cavity. The amount of liquid which is removed depends on the energy of the pulse as well as on its shape. The amount of water which fills the cavity between pulses depends on the time which elapses between pulses, on the physical characteristics of the liquid as well as on the height of the cavity. Using a simplified model which assumes that the only force behind the filling process is hydrostatic pressure, the following relation can be obtained between the height of the cavity which can be achieved—h, the pulse repetition rate—f and the energy per pulse—E_p:

$$E_p = (A/f)\, h^{3/2} \qquad (1)$$

Where A is a constant which depends on the mechanism behind the removal of the liquid. Both the model and the experiments show that it is possible to transmit trains of laser pulses having the above characteristics through opaque liquids [9].

Irradiation of Tissue Underwater

The cavitation effect provides a means of irradiating tissue which is immersed in water. A laser beam having the proper characteristics, as described above, "drills" a cavity in the liquid, through which the remainder of the beam energy traverses to the tissue. We believe the liquid will provide a better medium than air for cooling tissue and at the same time will serve as a "mask" which will filter the tails of the Gaussian beam (see Fig. 1) thus providing a cleaner cut in the tissue. A series of experiments was thus performed in order to evaluate the thermal damage caused by irradiation to a sample of tissue immersed in liquid, as compared to that caused to the same tissue in air.

MATERIALS AND METHODS

All experiments were performed on fresh bovine cornea which was stored in normal saline

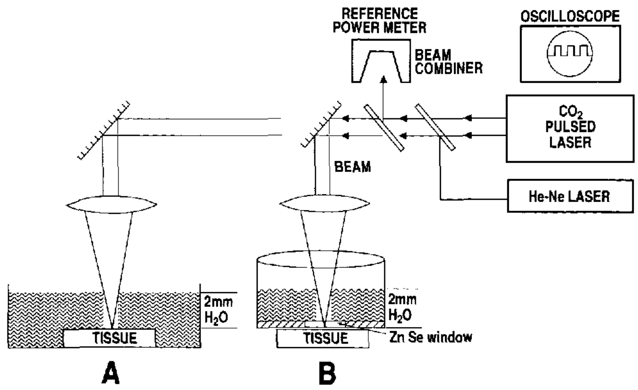

Fig. 2. Experimental system for evaluating effects of irradiation through water on thermal damage. **A:** Tissue is immersed in 2 mm of water and irradiated by a CO_2 laser beam. **B:** Tissue is irradiated in air, but the beam passes through a container that holds a 2 mm layer of water through which the beam must traverse.

solution until immediately before laser irradiation. The cornea was selected for its homogeneity and smooth surface, thus eliminating the need for adjustment of the focal point due to the geometry of the tissue. The cornea were fixed onto a mount so as to achieve a smooth uniform surface.

Two sets of experiments were performed. In the first set of experiments, the cornea were immersed in 2 mm of water and irradiated by a CO_2 (Apollo model 580) laser at various irradiation conditions using the setup described in Figure 2A. In the second set the cornea were irradiated in air under the exact same irradiation conditions using the setup shown in Figure 2B.

It is reasonable to assume that a beam which reaches tissue which is immersed in liquid, will be altered both in energy and in shape by its passage through the cavity. Thus, to be able to isolate the effect of immersing the tissue in water, it was necessary to be able to exactly reconstruct the beam profile at the exit from the cavity and to use that profile and energy to irradiate the tissue in air. Rather than measuring the beam profile and then attempting to reconstruct it via optical manipulation, we chose to insert a small container, the bottom of which was formed by a ZnSe window, which is transparent to the CO_2 laser radiation, in the beam path. The container was filled with water at a height of 2 mm as in the case of the water layer above the immersed tissue. The container was held 2 Mm above the tissue surface by a stable side grip. Thus, the beam that exits the container simulates exactly the one irradiating the immersed tissue. This experimental set-up allowed us to compare two cases, which differ only in the fact that the tissue is immersed in water and not to any changes in the beam profile or energy which may arise from the transmission through the cavity.

The CO_2 laser (Apollo model 580), capable of pulse durations between 0.01 Msec to 1 sec, was used to irradiate the tissue at average powers of 11, 17, and 25 Watts, frequencies ranging between 200 and 1100 Hz, and peak powers of 0.02–0.24 Watts. Average power delivery was measured by an external power meter (Coherent Radiation 201), Pulse duration and frequency were measured by an oscilloscope (Kenwood CS 1021).

A 25 Cm focal length lens was used to focus the CO_2 laser beam onto the upper surface of the liquid, achieving a beam spot of approximately 1Mm. A HeNe beam (Spectra physics 155) was used as a pointer. Tissue irradiation was performed in the pulsed mode changing, average power, pulse duration, and frequency. Lazing time was 2 sec. Following irradiation, the tissue was fixed in 10% buffered formalin for 48 hours, embedded in paraffin and then cut at 4 micrometer intervals. In order to investigate the thermal damage induced throughout the depth of the incision, sections were made along the vertical axis of the crater. We chose this plane because it demonstrates the full extent of the thermal damage along the beam path as opposed to sections along the horizontal plane that do not include the crater "shoulders," the zone of maximal thermal damage. The sections were stained with hematoxylin-eosin then examined and measured by light microscopy.

RESULTS

In several cases we noticed that due to the histological slicing, the epithelium tends to separate from the corneal parenchyma in the vicinity of the crater. We thus focused on measurement of the thermal damage width at the upper surface of the corneal parenchyma (Fig. 3).

In general, the damage produced by irradiation through water was less extensive than that produced by irradiation through air. Irradiation under water (Fig. 3A) markedly reduced the thermal damage at the upper edge of the parenchyma as compared to irradiation in air (Fig. 3B).

For the average powers measured as demonstrated in Figure 4, the dots represent tissue irradiated in air and the triangles represent tissue

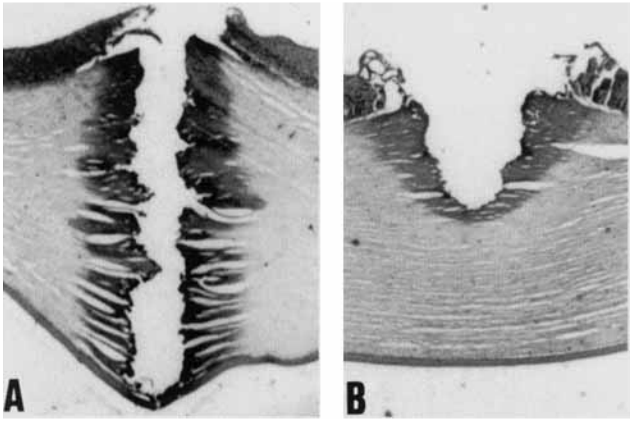

Fig. 3. Histologic preparation of cornea irradiated under saline (**A**), in air (**B**), power average-17 W, frequency- 800Hz.(H and E stained, magnification of X 40, thermal damage stains dark). Thermal damage width was measured at the upper surface of the parenchyma below the separated epithelium. In A the superficial part of the crater closer to the fluid shows narrower thermal damage width.

irradiated under water, for each average power "water" points were all grouped together as were the "air" points, before statistical analysis was performed. A two way analysis of variance (ANOVA) showed a highly significant difference ($P < 0.001$) between lesions produced in water versus air, for all irradiation conditions. The thermal damage received at 25 W was found to be significantly larger ($P < 0.01$) then that at 11 or 17 W regardless of the medium on the tissue. No difference in thermal damage could be found between variable frequencies or peak powers used within the same power average (Fig. 4.)

It is clear that the thermal damage surrounding the ablated region was markedly reduced when irradiating the cornea underwater as opposed to irradiating it in air. Furthermore, in the immersed tissue, thermal damage was consistently narrower in the superficial part of the crater compared to the deep part (Fig. 3A).

DISCUSSION

Thermal damage is part of the photo-thermal interaction between the CO_2 laser and tissue. The ablation process itself, is the extreme case of thermal damage, where the tissue is heated to sufficient temperatures for a long enough time to be ablated. However, in the regions further away from the beam center, thermal transport from the ablated region as well as the "tails" of the Gaussian beam cause heating which is sufficient to cause irreversible damage, but, insufficient to cause ablation. Thus, thermal damage can not altogether be eliminated.

Many ways have been suggested and used in trying to reduce the unwanted thermally damaged layer surrounding the incision. These include optimizing both temporal and spatial characteristics of irradiation, and cooling of tissue before and after the irradiation process using air or cool water [7,8].

In this study we isolated the cooling effect of water, where the beam that reached the tissue passed through 2 mm of fluid, the only difference between the two experimental sets was the presence of fluid vs. air on the tissue surface. As we have shown, immersing tissue in water during the irradiation process helps to reduce the thermal damage which surrounds a crater produced by a CO_2 laser beam. We think that the main mechanism responsible for this reduction is the cooling of tissue by water, during the irradiation process, and immediately following. This cooling effect is probably related to the distance from tissue surface (Fig. 3A), as the crater bores deep into the tissue, cooling becomes ineffective. Water has a thermal conductivity two orders of magnitude larger than air, so that the tissue can cool more efficiently by giving off heat to the surrounding liquid. Consequently, less heat is transported to the area around the incision, the thermal damage caused is affecting a smaller volume of tissue.

In addition to the cooling effect, we assume, there is also a filtration effect at work, contributing to the reduction of the thermal damage that is caused by the Gaussian "tails" of the beam. This effect was not studied here. In order to isolate and investigate the filtration effect, one should measure the power average reaching tissue surface after cavitation through a ZnSe container filled with water, irradiate the tissue with the same power average through a ZnSe container filled with air and compare the thermal damage in both cases.

The fact that at higher power average (25 W) thermal damage was larger, even when using the cooling effect, can be explained by the penetration of larger segments of the Gaussian "tails" through the cavity.

The two main causes of thermal damage surrounding incisions made by the laser beam, during photo-thermal interactions, are thus the Gaussian tails and heat transport to the surrounding tissue. We have shown that irradiating

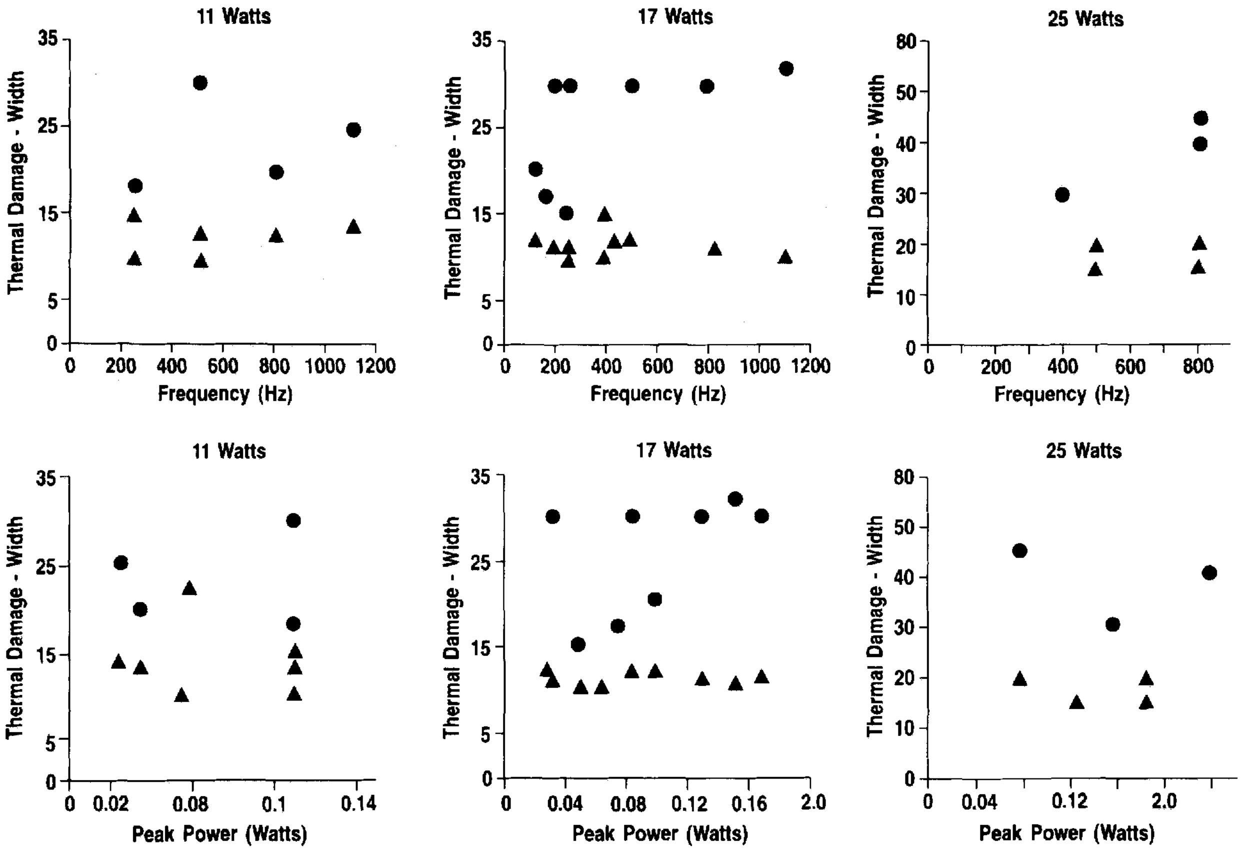

Fig. 4. Width of the thermal damage vs. laser frequency and peak power. Data were measured at three different average powers. Dots—tissue irradiated in air. Triangles—Tissue irradiated under water.

tissue through a layer of water can reduce thermal damage by modifying the latter effect.

CONCLUSIONS

We found the crater made in fluid to produce less thermal damage then that made in air under the same beam conditions. This permits the conclusion that laser irradiation of tissue immersed in liquid, using the cavitation effect, reduces the thermal damage involved.

Since the cooling effect was isolated in this study, we assume this process results from a more efficient heat transport in the presence of fluid, and suggest using the same set-up with fluid below room temperature to reduce thermal damage even further.

The practical importance of this method is that flushing tissue, with a cooling fluid, while irradiating it, will enable precise and clean cutting, as needed in medical applications: Plastic surgery, Neurosurgery, and Ear, Nose, and Throat surgery. In addition, the cavitation effect is an opening for the use of CO_2 laser through fluids that were previously "opaque" for it, enabling the application of CO_2 laser in urology, in the urinary bladder and in cardiology, in blood vessels.

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